Update on SINAP TMSR Research

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MSR Workshop 2016
ORNL, Oct.4-5 2016

Outline

- Project overview
- Highlight-2016
  - Th-U fuel cycle
  - Materials
  - Reactor engineering
- Summary

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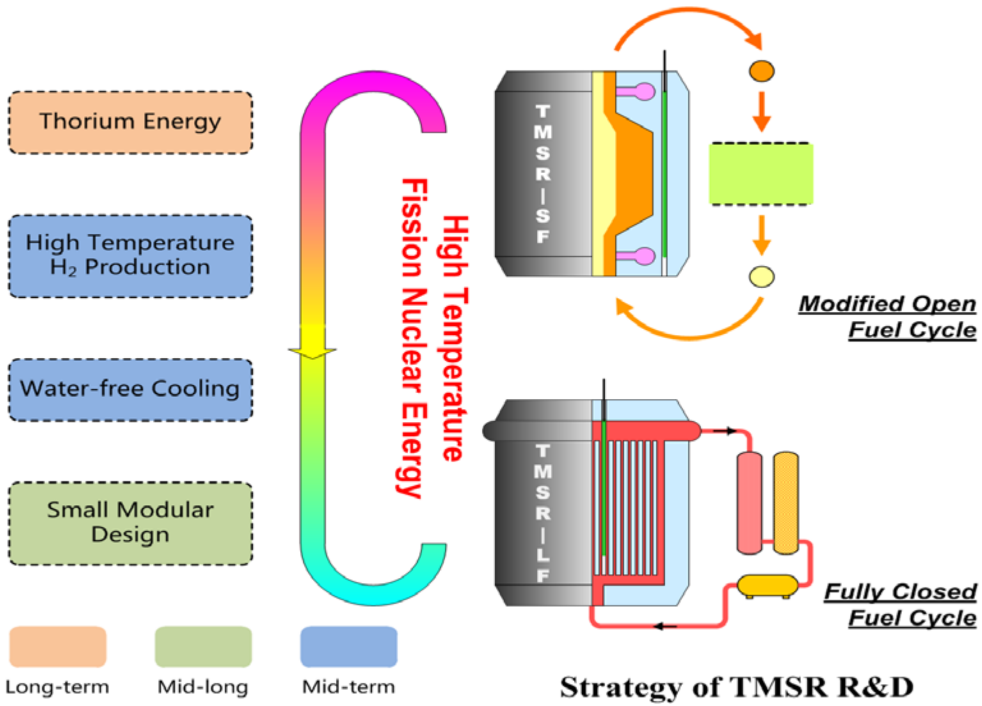
China's TMSR Project

- **TMSR: Thorium Molten Salt Reactor Nuclear Energy System.**
- **Long term goal: Develop TMSR for Thorium utilization and Low-C energy application in 20-30 years.**
- **The phase I program (so called pioneer program) was initiated by the Chinese Academy of Sciences (CAS) in 2011.**

TMSR Reactors and Applications



Strategy of TMSR R&D

Th Energy :

- Long-Term Supply of Nuclear Fuel

MSRs :

- Elevated Safety
- Higher fuel efficiency
- H-T nuclear energy

- TMSR-LF (Liquid-Fuel): Optimized for utilization of Th with Pyro-process.
- TMSR-SF (Solid-Fuel): Optimized for high-temperature based hybrid nuclear energy application.

Goals of TMSR Pioneer Program

- Develop Th utilization scheme based on MSRs and pyro-process. Develop pyro-process flow sheet.
- Design, construct 2 test reactors (2MW liquid fuel, TMSR-LF1, 10MW solid fuel, TMSR-SF1).
- Develop materials, salts, fuel, components, instrumentations etc. for test reactors.
- Licensing and site selection of test reactors.
- Build up R&D platform and Experienced team for future TMSR research and development.

Summary of R&D Activities up to Now

Engineering developments

- Test reactors design, safety analysis and licensing. Test reactor components and instrumentations. Tritium control technique.
- Materials (alloy, graphite, C-C, Fluoride salts, fuel, ^{7}Li etc.) fabrication, processing and qualification.
- Molten salt related mechanics, test loops.
- Pyro-process techniques and equipment.
- High temperature nuclear hybrid energy system design, hydrogen production prototype.

Researches

- Physics of Th-U fuel cycle, Neutronics, T-H, reactor modeling, basic data, codes developments; design study of small modular MSRs.
- Basic sciences behind material fabrication, processing and performance (e.g. mechanic strength, molten salt corrosion, radiation damage), and chemical separation.

Major R&D progress had already been presented in the workshop held last October.

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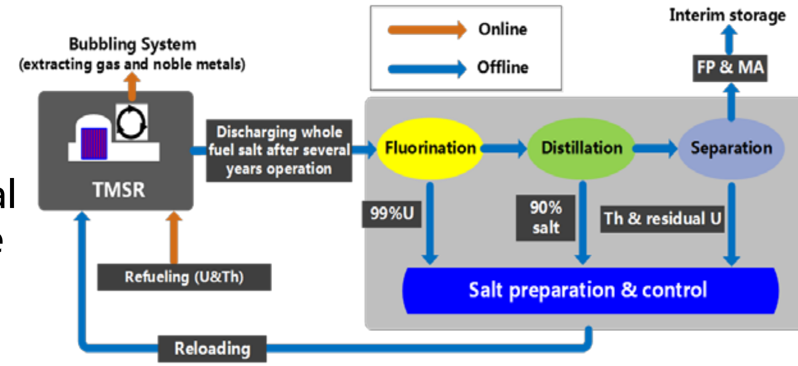
Th-U fuel cycle: 3-step strategy

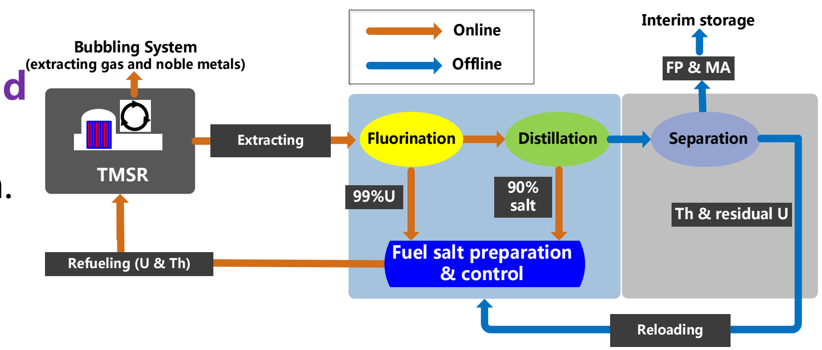
➢ Step1: Offline batch process

- Fuel loading: LEU+Th (transition to Th cycle); U3+Th (future standard fuel)
- Online refueling and remove gaseous FPs. After several years' operation, discharge whole core fuel salt, offline extract U&Th and reload to core for operation.
- FP&MA for temporary storage.



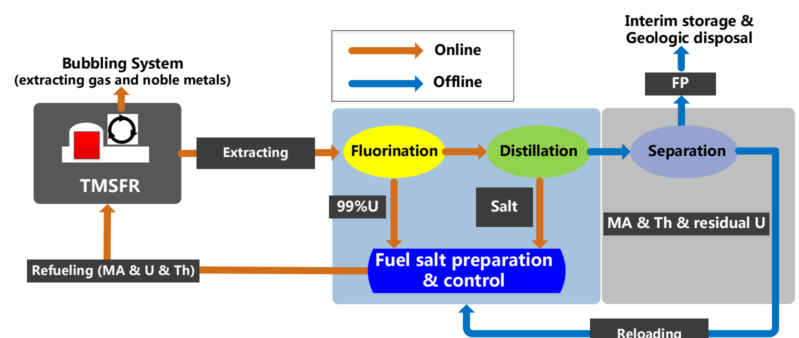
➢ Step2: Online process, quasi closed cycle

- Online remove gaseous FPs. **Online extract and reload U to enhance fuel utilization ratio.**
- Offline batch process to recycle salt, residual U and Th.
- FP&MA for temporary storage.



➢ Step3: Fully closed fuel cycle

- Online remove gaseous FPs.
- Online extract and reload U.
- **Offline extract TRU and reload to reactor.**
- **Recycle mode: Breeders / Burners. All heavy elements are recycled.**
- Geologic disposal: only FPs and a small amount of U and MA loss from reprocessing

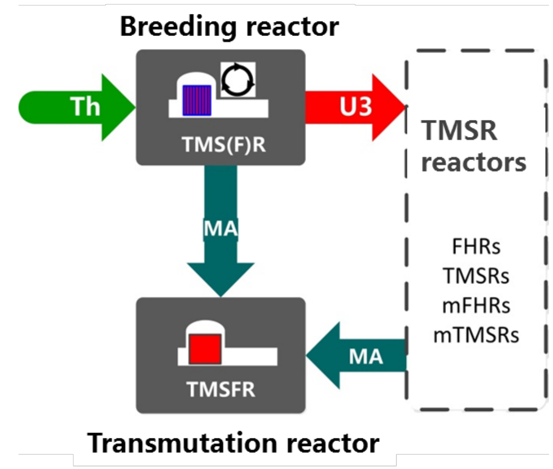


Target performance of "three steps"

Characteristics	Step 1	Step 2	Step 3
Fuel reprocessing	Batch processing	Continuous processing	Continuous processing + MA re-injected
Fuel utilization efficiency（%）	1~5	~45	55~100
Radiotoxicity （Sv/GW.y）	$\sim 1.0 \times 10^7$	$\sim 5 \times 10^6$	1×10^5
Th fission fraction（%）	~24	50 - 100	100
Convert Ratio (CR)	0.6-0.8	0.8-1	≥ 1
TRU transmutation rate（%）	/	/	> 95

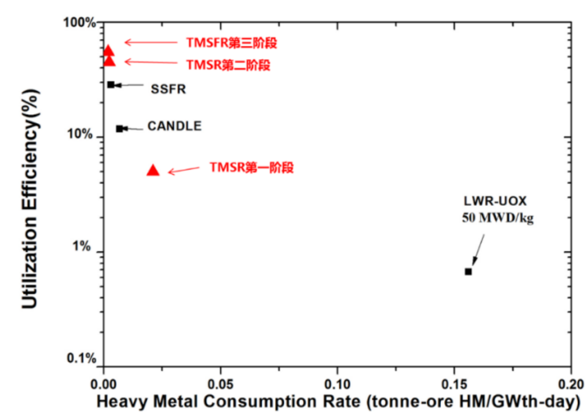
Th-U fuel cycle: 3-step strategy

The third step can fully incinerate the MA from the previous two steps, realizing the fully closed fuel cycle.



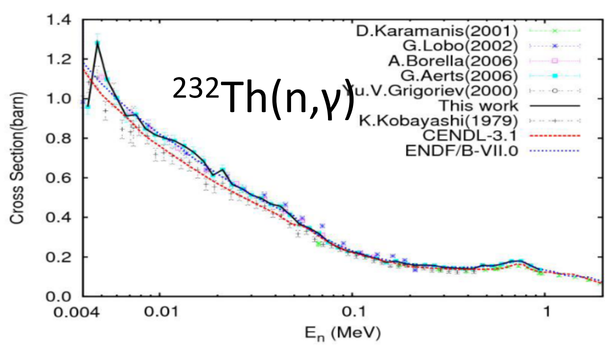
- **The breeder reactors supply U233 for series of commercial reactor fleets**
  - High breeding, ensuring the sustainable utilization of Th for the TMSR family;
  - The fuel utilization efficiency of each generation can reach 40%-60%。

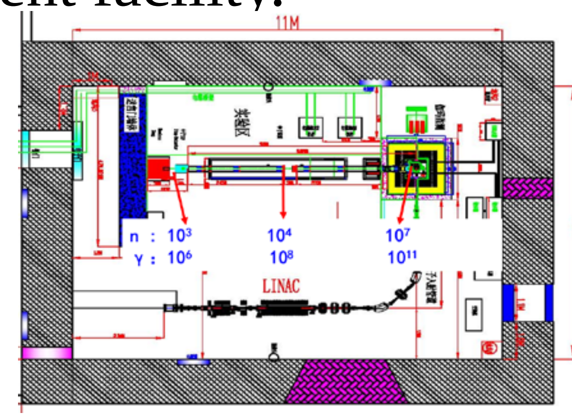
- **The transmutation reactors clear up the wastes from the commercial reactors**
  - The transmutation rate can reach to 95%
  - After multi-generations , the fuel utilization efficiency can approach to 100% and with minimum radiotoxicity emission.



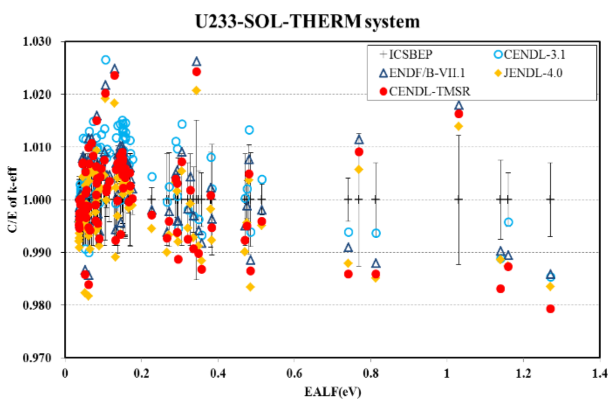
Th-U fuel cycle: Nuclear Data

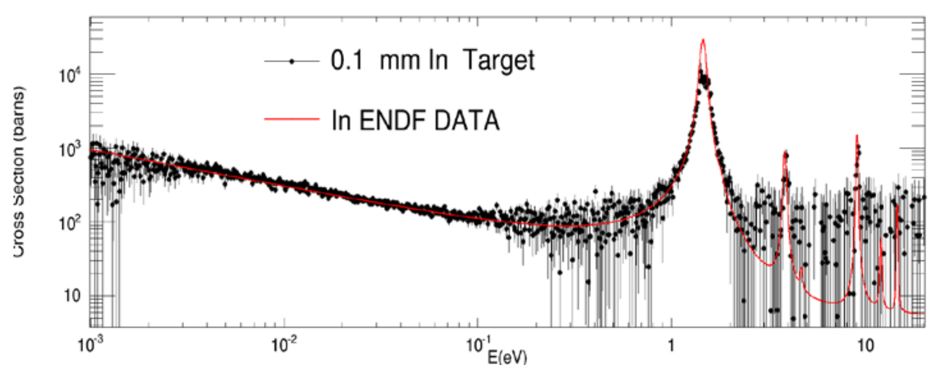
- Establish the special nuclear data library for TMSR(CENDL-TMSR-V1), which includes 403 nuclides.
- Commissioning of electron LINAC neutron source and neclear data measurement facility.



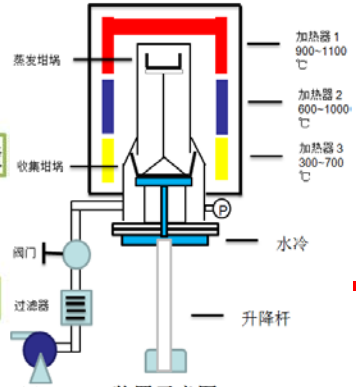


	设计指标
平均流强/mA	0.1
电子能量/MeV	15
功率/kW	1.5
靶	钨
脉冲频率/Hz	1-266
中子脉冲宽度/ns	3-3000
飞行距离/m	1-5
分辨(@MeV)%	<1
中子通量/$s^{-1}cm^{-2}$	10^5
中子产额10^{13}/s^{-1}	0.4





Th-U fuel cycle: pyro-processing technology

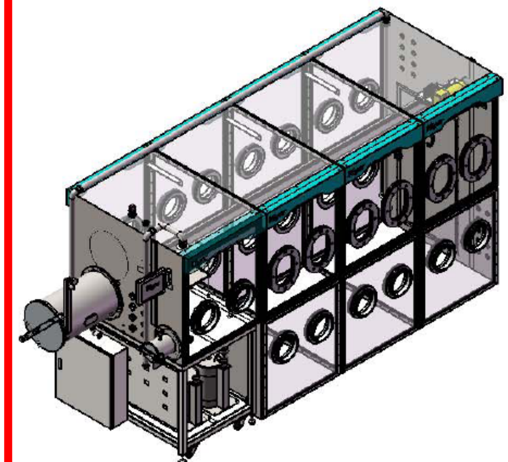


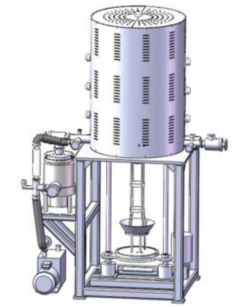
装置示意图

Molten salt distillation facility designed for FLiBe, kg level, salt recovery rate > 98% for Flinak

F_2 supply | Fluorination | monitors | Product recovery | Tail gas

High temperature fluorination facility, kg level
U recovery recoveray rate >95%





Integrate pyro processing line under construction

Th-U fuel cycle: electrolytic separation

Solve the direct reduction problem of $U^{4+} \rightarrow U$ by prereduction method. Dendritic U metal was obtained.

U^{4+}

Electrochemical prereduction

Low effeciency

$3UCl_4 + U \rightarrow 4UCl_3$

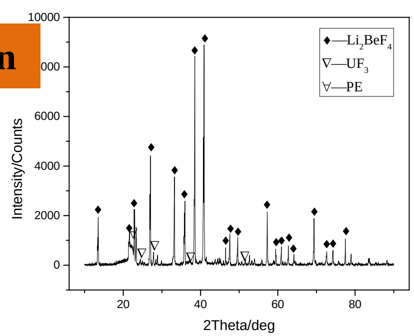
$\triangle G = -387.4\ kJ\ mol^{-1}$ (700 K)

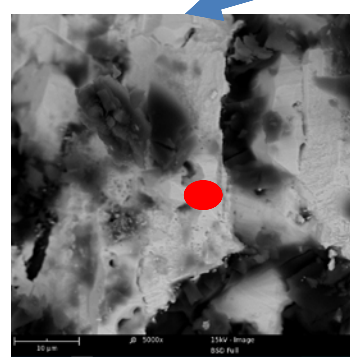
U^{3+}

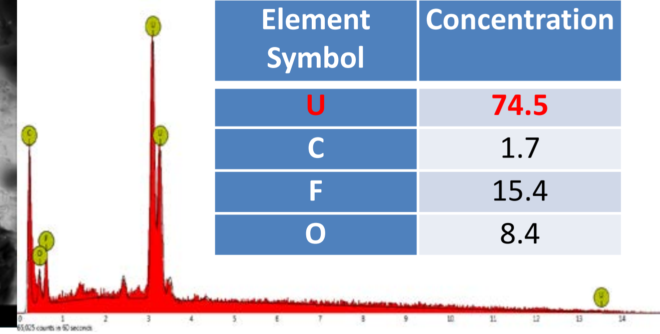
electrolysis

U (cathode)

Li metal Prereduction



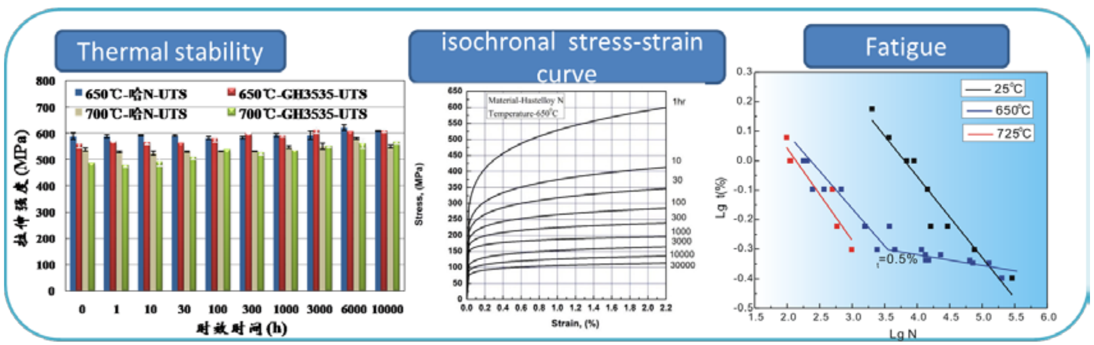


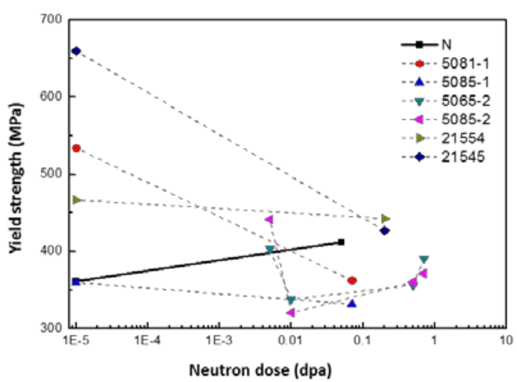


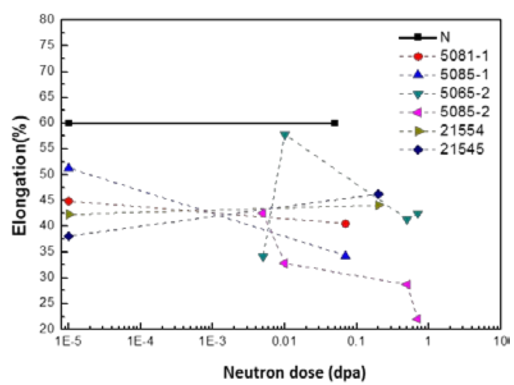
Element Symbol	Concentration
U	74.5
C	1.7
F	15.4
O	8.4

Materials: Alloy

- **GH3535 fabrication, processing:** 10t ingot and 3-m diameter ring rolled piece manufactured, welding procedure fixed.
- **Material data base** is in construction. Extensive experiments are in progress to produce long time mechanical performance data **(>10000h up to now)**. Irradiation tests are also in progress.







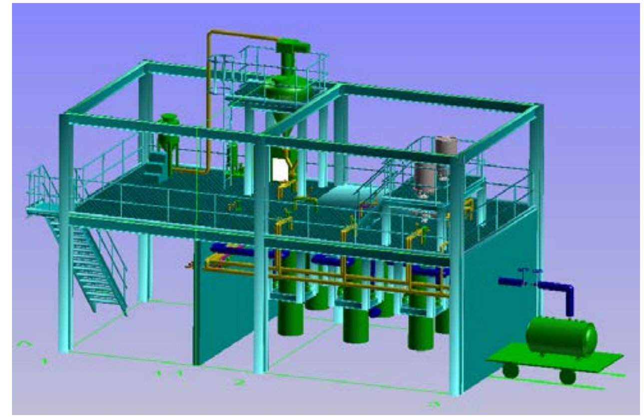
PIE at room temperature

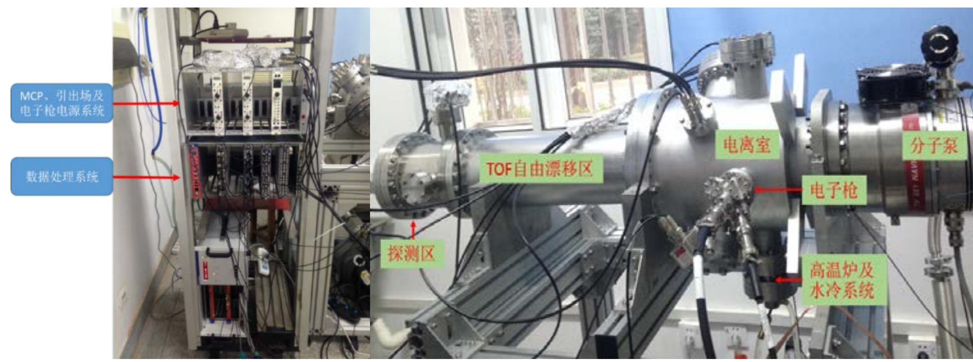
Materials: Fine grain graphite

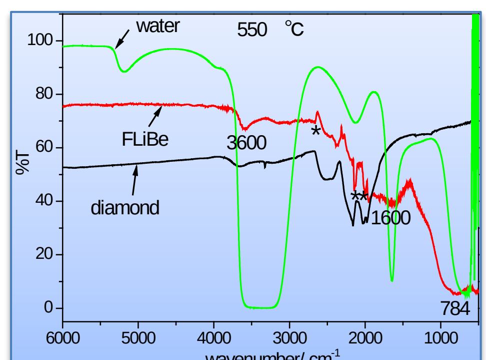
- Fabrication technology progress: improve rate of finished products, improve fracture toughness, fabricate larger block (1400X600X350mm)
- Material Irradiation tests and performance tests after irradiation have been planned. The irradiation will be start soon in high flux reactor of China.
- Experimental study for graphite irradiation together with molten salt will be carried out in collaboration with MIT Reactor Lab.

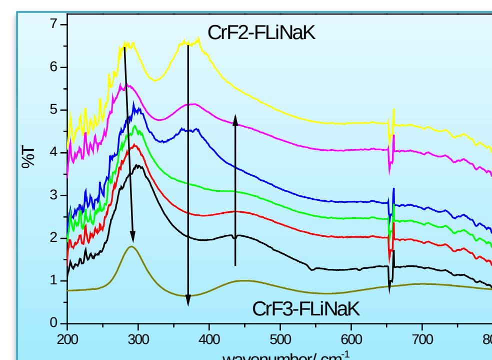
Materials: Fluoride Salt

- Mass production of high purity FLiNaK salt: A production line able to produce 10t salt per year has been constructed.
- Facility for kg level FLiBeThU fuel salt production has been designed.
- Experimental facility for study molecular and cluster structure of salt vapour.
- New results of spectroscopy study.



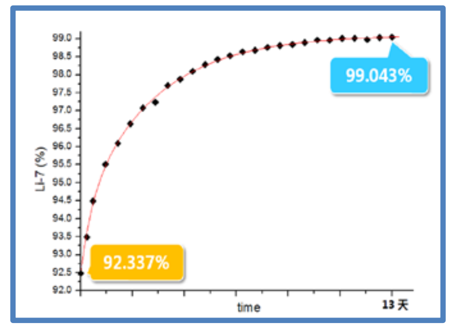


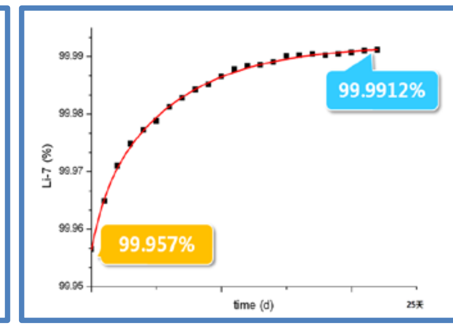


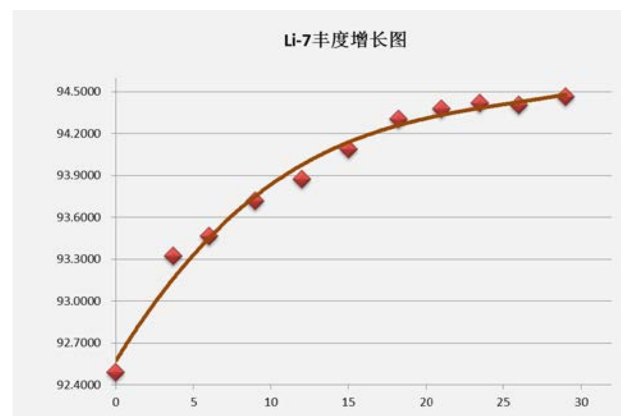


Materials: Extraction separation of $^{6}Li/^{7}Li$

- 2011-2014: Develop new methods, small scale demo in laboratory. 160 cascade stages, ϕ20mm centrifugal extractor. 99.99% ^{7}Li can be produced.
- 2015-2016: Mid scale (20kg ^{7}Li/a) demo and test. 40 cascade stages, ϕ100mm centrifugal extractor. 7Li abundance increased from 92.49% to 94.46%.
- The plan of large scale factory (tone/a) in under evaluation.



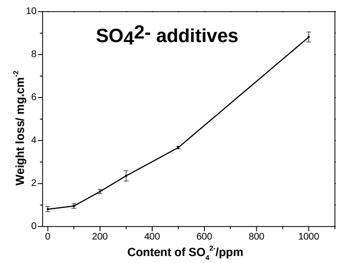


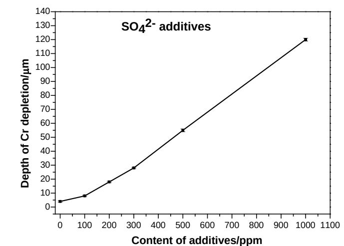


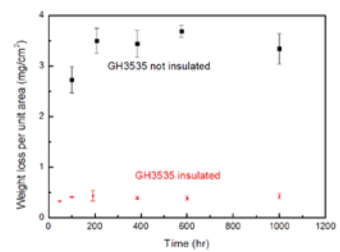
Materials: corrosion control

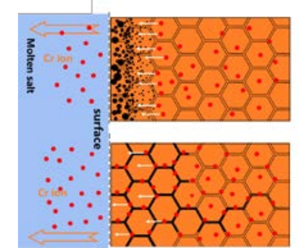
- Corrosion rate about 2um/a was observed for N alloy in highly purified FLiNaK molten salt (static) .
- Corrosion behavior and mechanism
  - Cr deffusion.
  - Contamination effects: SO_4^{2-}, metal ions.
  - Corrosion acceleration of alloy with graphite? Electric dipole corrosion, contaminants effects.
- Corrosion protection for SS316
  - Different corrosion mechanism of N-alloy and SS. Uniform diffusion vs. grain boundary diffusion
  - Corrosion protection by adding "buffer pair" in salt.
  - Corrosion protection by surface treatments.

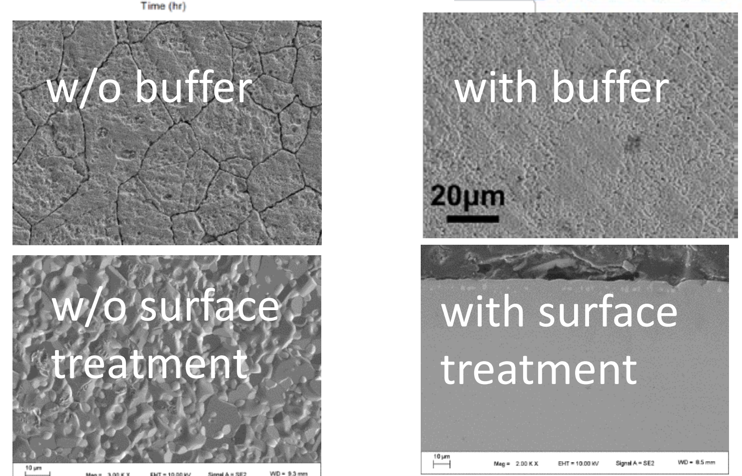
Depth of Cr diffusion layer, different salt purity











Changed to predictable uniform diffusion

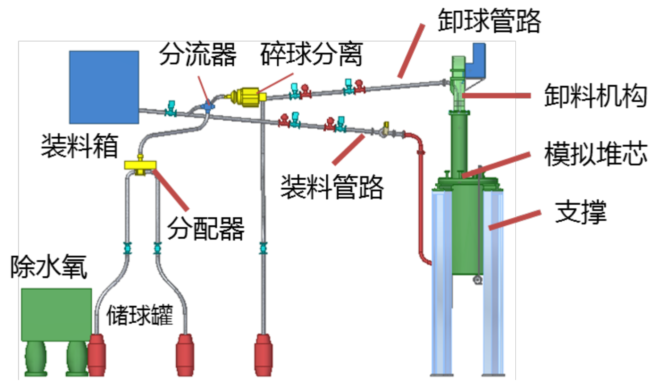
Reactor engineering: test platform

Comprehensive test platform has been designed and in construction, for non-nuclear testing of MSR materials, components, instrumentation and test reactor design.

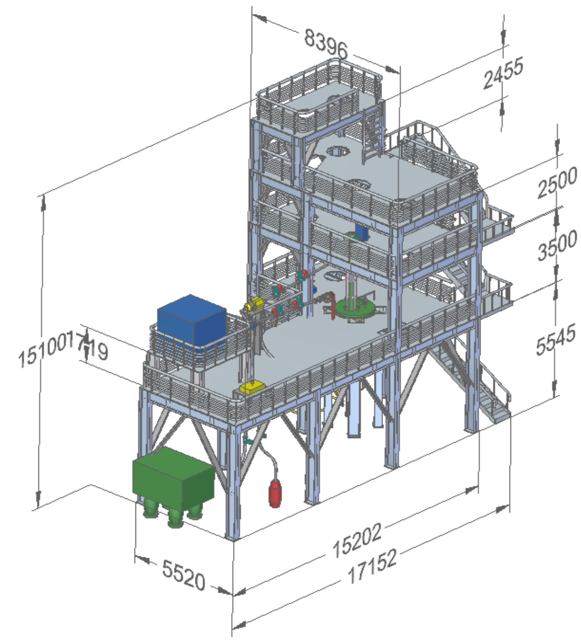
- Test benches for TMSR-SF1 components: Molten salt pumps, Control rod systems, fuel pebble circulating system etc,
- Test benches for MSR instrumentation: temperature, level, pressure, flow rate and neutron detectors.
- Simulate reactor (TMSR-SF0) based on TMSR-SF1 design.

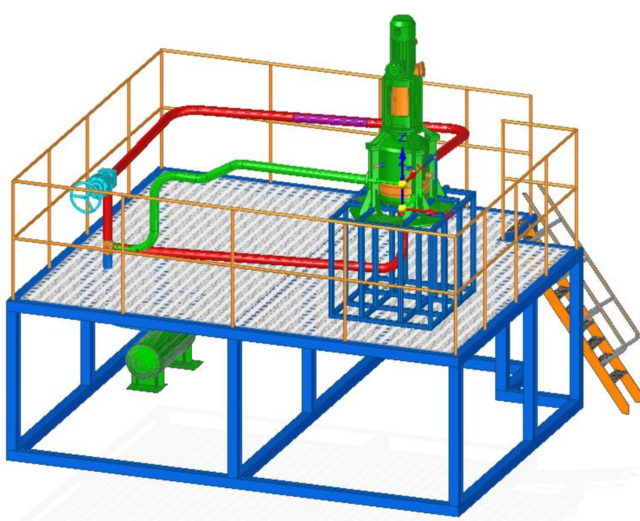
Reactor engineering: Component test benches

Control rod test bench. Simulate design and service condition in TMSR-SF1



Fueling, defueling and pebble circulating simulation in molten salt condition.





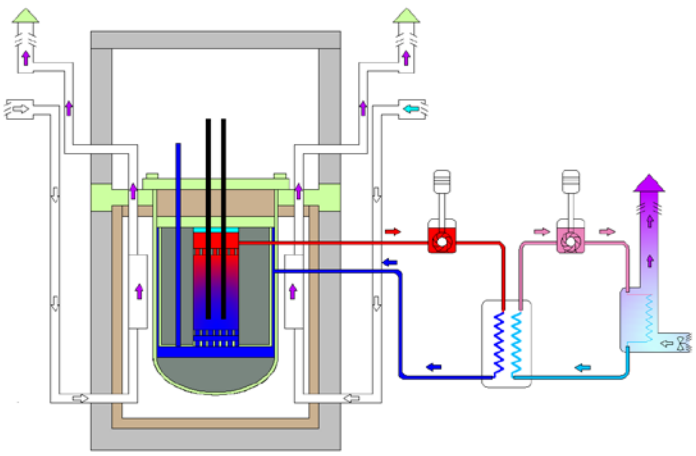
Salt pump test bench

Working medium	FLiNaK molten salt
Temperature	500~700℃
Flow rate	≤500 m^3/h
Pump lift	≤40m
Power	≤150kW
Pressure	1MPa

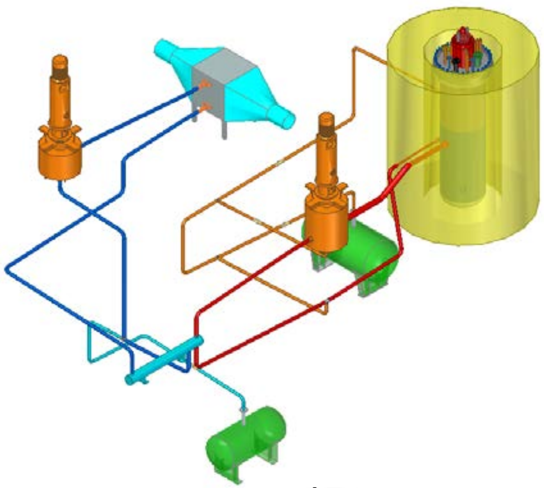
TMSR-SF0 is a simulator of TMSR-SF1 (1:3 in geometry), with various purpose:

- **Verification** test of the T-H design and safety design of TMSR-SF1;
- Test the feasibility of some SF1 engineering designs and the reliability of design calculations;
- To **benchmark** the validation of T-H and safety analyzing **codes** for TMSR-SF1 and future FHR.
- To study the steady and transient behavior of FHR by simulating various event of SF1.
- To be a **comprehensive demonstration and testing platform** for materials, component and system techniques that TMSR developed during past years.
- To be a **training platform** for TMSR-SF1 operation.

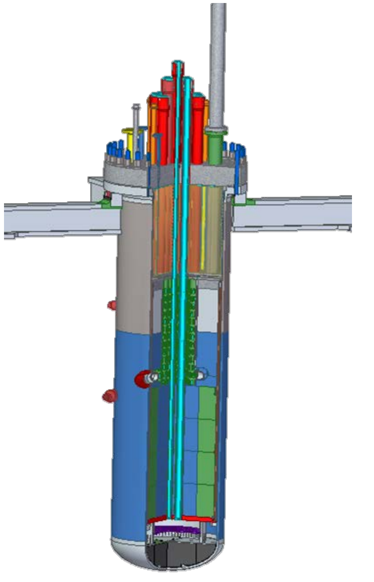
Reactor engineering: TMSR-SF0

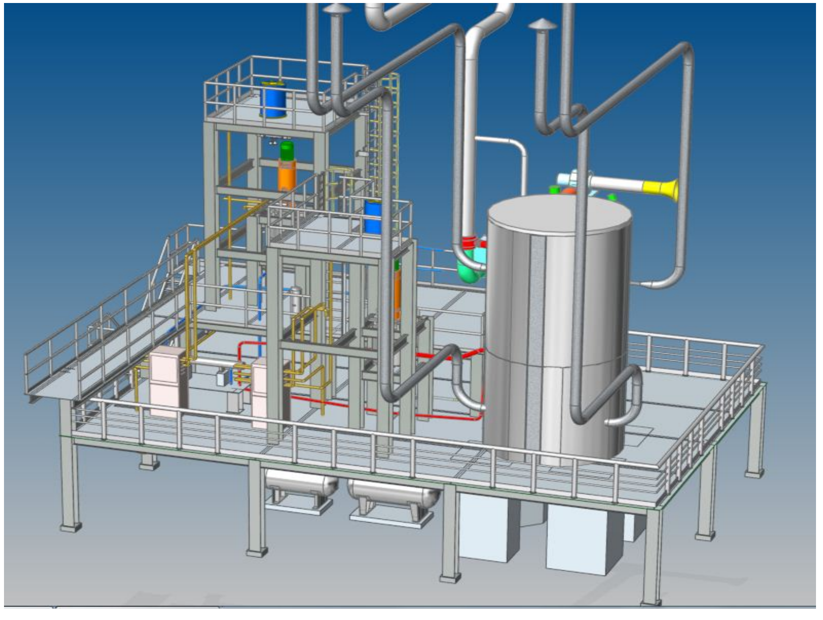


Schematics of principle



System layout





Overall installation drawing

TMSR- SF0 Design Parameters			
Electric Heating Rated Power @ Core	370kW	Design Temperature @ Main Vessel	700℃
Temperature of Molten Salt @Reactor Inlet	600℃	Design Pressure @ Main Vessel	0.5MPa
Temperature of Molten Salt @Reactor Outlet	650℃	Design life	10 year
Mass Flow of Molten Salt @ Primary Loop	0-10.0 kg/s	Mass Flow of Molten Salt @ Second Loop	0-12.2 kg/s
Cover Gas @ Primary Loop	Ar	Rated Power of Passive Exhaust System	12.8 kW
Molten Salt @ Primary Loop	FLiNaK	Molten Salt @ Second Loop	FLiNaK

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Summary and Outlook

- TMSR Project has made big progress in wide range of basic research and engineering development. However, the plan to build test reactors is postponed, instead, a simulate reactor will be built.
- The recent announced 13th five-year plan of CAS requires to build a 2MW molten salt test reactor for Th-U fuel cycle experiments.
- Chinese government will continue to support the long term R&D of Th utilization.
- SINAP is making new plan towards TMSR commercialization, and making effort for industrialization of molten salt related techniques.

Thanks for your attention!